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A SPACE RADIATION ENVIRONMENT SIMULATOR FOR THE EVALUATION OF SOLAR CELLS

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ABSTRACT: A facility for studying the properties of solar cells and other optically sensitive devices under a wide range of environmental conditions such as could be found on extra-terrestrial space missions has been developed at the NASA Goddard Space Flight Center. The system includes control of temperature, vacuum and solar irradiation while irradiating a 23 cm by 23 cm array of samples with 4 MeV protons or electrons. Typically the samples can be controlled in temperature between -170°C and 150°C, while a shroud, used to control radiative coupling, can be independently controlled between -196°C and 150°C. The vacuum system, which is virtually free of hydrocarbon contamination, will evacuate the chamber to less than 1×10^{-8} torr in less than 4 hours. A 400 1/s Noble Vac-Ion pump backed by a titanium bulk sublimator and a titanium filament evaporator has been designed to accommodate the large gas loads possible during irradiation. A 4.2 KW compact Xenon arc solar simulator provides a close match to the solar spectrum from low irradiances to an irradiance of four solar constants. An automatic data acquisition system modified to generate digital solar cell I-V characteristics is used to collect data in a form suitable for computer processing.

KEY WORDS: space simulation, space radiation, solar cells, tests, thermal control, high vacuum.

INTRODUCTION

A facility for the in-situ testing of solar cells and other optically sensitive devices under a simulated space environment has been built and is in use at the Goddard Space Flight Center of NASA. The system is capable of irradiating a 23 cm × 23 cm array of solar cells with both particulate radiation (protons or electrons) and simulated solar radiation while being maintained under a vacuum of 10^{-8} torr or less and controlled in temperature over a range of -170°C to 150°C. Data acquisition is accomplished automatically using a conventional system with a number of special modifications.

CHAMBER DESIGN

A plan view of the system is shown in Figure 1. The main chamber is a stainless steel (304) cylinder 45 cm in diameter and 203 cm long with a Wheeler flange holding the sample holder and all of the electrical feedthroughs at one end and an entrance port for the particulate radiation at the other. A port with a u.v. grade quartz window is located at right angles to the particulate beam adjacent to the beam entrance port. The use of a slightly off-axis turning mirror permits the simultaneous irradiation of the samples by photons and protons or electrons. The length of the chamber is needed to accommodate the divergence of the particulate beam. A cryogenic shroud that covers the region from the sample holder to the turning mirror is used to prevent unwanted radiative coupling. The sample holder can be rotated about 5° on an axis normal to the plane of the particulate beam and the simulator beam so that measurements can be made with each of the components normal.

VACUUM SYSTEM

All of the high vacuum pumping equipment is located below the main chamber (Fig. 2). The various pumps used are listed in Table 1 along with their pumping speed and range of operation. The basic pump is a 400 l/s Noble Vac-Ion[1] pump that is assisted in its various ranges by a titanium filament evaporator and a titanium bulk sublimator. The roughing system is mounted on a separate cart and is connected to the system by a flexible line. It consists of a gas aspirator and three cryogenic sorption pumps. Under ideal conditions (system

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[1] Varian Assoc. Palo Alto, Calif.

not opened to atmosphere for too long) the chamber can be evacuated from atmosphere to 1×10^{-8} torr in less (Fig. 3) than four hours. With the exception of one viton "O" ring used to seal the quartz window all openings are closed with copper gaskets to provide a hydrocarbon free system. The system pressure is monitored by a nude ion gauge located in the main chamber. The introduction of high energy protons into the system during irradiation of the solar cells could provide for a substantial gas load both from induced outgassing of the chamber walls and substrate and from the protons themselves. Fortunately the titanium bulk sublimator has an enormous pumping speed in this region so that the pressure can be kept under control for these peak gas loads.

SAMPLE PLATEN

Solar cells to be irradiated are mounted on a temperature controlled copper platen (Fig. 4) located at the end of the chamber. The platen size is 23 cm × 23 cm and can accommodate about 50 solar cells at one time. A series of 9 Faraday cups are mounted at various points on the platen so that their apertures are in the plane of the solar cells. The walls of the Faraday cups are fabricated from tungsten so that the wall thickness could be made greater than the range of 4 MeV electrons. The Faraday cups are used to monitor the uniformity of the radiation over the surface area. Thermocouples are mounted on some of the cells to record the actual cell temperature during the experiment.

The wires used to transmit the cell characteristics are run along the platen surface and are shielded by copper guides. The thermal coupling of the solar cells can be monitored under various experimental conditions by measuring the open circuit voltage. It has been found that the cell junction temperature can be kept within 3 or 4°C of the sample platen with 1400 W/m^2 (approximately one solar constant) incident on the solar cell. This is about what one would expect based on the published values of the thermal conductivity of silicon.

TEMPERATURE CONTROL SYSTEM

The thermal system is used to control the temperature of the cryoshroud and the sample platen. Several critical design constraints had to be met. These were:

1. Rapid shroud temperature response over a range of -170°C to 150°C.

2. A shroud gradient of less than ±5°C over this temperature range under a distributed load of 1400 W/m^2.
3. Accurate shroud temperature control over the desired temperature range.
4. Rapid specimen temperature response.
5. Accurate specimen temperature control (±2°C) while being subjected to varying incident solar radiation intensities.

In addition both the shroud and the sample platen had to have an accumulated leak rate that was less than 1×10^{-9} ml/s referred to standard pressure and temperature over the operational temperature range.

The thermal conditioner for the shroud consists of a pumped gaseous nitrogen loop, a series of heaters, and a gaseous nitrogen to liquid nitrogen shell and tube heat exchanger. The entire system is housed in an equipment cabinet 76 cm wide, 137 cm long and 183 cm high. A block diagram of the system is shown in Figure 5.

A three stage centrifugal blower is used to circulate approximately 104 l/s (220 CFM) of nitrogen gas through the system. Modulating butterfly valves proportion the gas flow through the heat exchanger. This variation in flow combined with a variation in power input to the heater produces a very precise means of effecting temperature control. There is also a large potential heat source or heat sink reserve. The response time and temperature overshoot of the system can be minimized by biasing the system source and sink against each other.

Rapid transients require that system mass be minimized. This is especially critical in the heater design since this element runs at the highest temperatures of any system component. The system heater shells are fabricated from thin wall stainless steel tubing 7.6 cm in diameter. Each heater module contains a 1.6 KW quartz infra red lamp and a set of thin aluminum fins. The fins are radiatively heated by the infra red lamp and are convectively cooled by the gaseous nitrogen stream. The weight of the heater extended surface is approximately 450 g.

The system heat sink is a liquid nitrogen boiler. Gaseous nitrogen is pumped through the tube side of the shell and a tube heat exchanger. The shell side of the unit is flooded with liquid nitrogen. The liquid level is maintained by the use of a temperature probe, controller, and a solenoid valve to permit filling from an external reservoir. Boil-off from the liquid nitrogen is mixed with the exit gas flow stream to further lower the circulating gas stream temperature. A pressure relief valve is located in the main gas stream to prevent excessive pressure buildup either from the introduction of boil off gas or from gas expansion during loop temperature up-transients. The relief valve maintains the gaseous nitrogen loop pressure at 21 KN/m^2 (3 psig).

The shroud thermal system tests showed that the system met the design goals. The transient performance of the system is shown in Figure 6.

To meet the temperature control requirements of the sample platen stated previously requires the use of a secondary cooling medium to eliminate the temperature rise that would otherwise result from the incident radiation.

It was desired to have a work surface temperature change capability of -170°C to 150°C. Conventional mechanical refrigeration temperature control techniques were examined and discarded as being too massive and slow in response.

The sample platen is shown in Figure 4. The surface that the samples are mounted on is made of 1.3 cm thick copper plate to obtain uniform temperature distribution. Heat removal from the platen is accomplished by conduction to a liquid nitrogen boiler and heat sink. Heat addition is provided by the use of four (4) 300 W infrared quartz lamps. The conduction path between the liquid nitrogen boiler and the platen is a square box section fabricated from stainless steel. The dimensions of this section are carefully selected and controlled. The infra red lamps are mounted inside copper "U" sections which are welded to the conduction path box section. The resultant thermal network provides the rapid response and ability to absorb varying amounts of incident flux without changing the surface temperature outside the design limits. Platen temperature control is provided by sensing the surface temperature, comparing it to a setpoint temperature, and varying the power input to the infrared lamps to effect a balance. A schematic representation of the system conduction paths and their electrical analogues is shown in Figure 7. The results of the system transient tests are shown in Figure 8.

RADIATION SOURCE AND BEAM OPTICS

The radiation source initially employed was a horizontally mounted 4 MeV Dynamitron[2] that was located in a shielded room adjacent to the environmental chamber. The Dynamitron, a d.c. charged particle accelerator, whose equivalent circuit is shown in Figure 9, is basically a set of cascaded vacuum tube rectifiers capacitively coupled to an r.f. power supply operating at 130 KHz. Two large r.f. electrodes, located along with the vacuum tubes and the ion source in a large pressure vessel filled with 1800 Kg of sulphur hexaflouride as an insulating gas (552 KN/m^2) (80 psi), induce an r.f. potential in a set of

[2] Radiation Dynamics, Westbury, N.Y.

corona rings causing a d.c. flow through the rectifiers and establishing a large potential at the output in the high voltage terminal. The capacitance from the r.f. electrodes to the pressure vessel and the previously mentioned inductive load result in resonant circuit operation.

An electron gun or duoplasmatron type ion source with an einzel lens, located in the high voltage terminal, provides an electron beam. The duoplasmatron and einzel lens is also used for the production of ion beams.

The beam is accelerated thru an evacuated accelerator tube across which the full d.c. terminal voltage appears. The mult-section glass and electrode acceleration tube assembly with an external resistance bleeder network provides a voltage gradient across the tube and establishes beam focussing by the tube electrodes. Typical base vacuum in the accelerator tube and its drift tube extensions is between 5×10^{-8} and 5×10^{-7} torr. Operational pressure is on the order of 10^{-6} torr. After acceleration from the terminal potential to ground the beam leaves the grounded pressure vessel and is transported to the target through evacuated stainless steel drift tubes with the aid of electrostatic and electromagnetic lenses and deflection elements as well as beam defining apertures.

The beam, after entering the beam transport system, is passed through a horizontal 46 cm circular pole face switching magnet. The magnet has a focussing effect in the horizontal plane but its primary function is to deflect the beam through a selected angle for transport to the target area in the adjacent room. In positive ion operation the magnet acts as a momentum analyzer insuring the purity of ion species and mono-ergic properties of beams reaching the target.

After deflection of the beam into a drift tube aligned with the center line of the environmental chamber, beam focussing and/or defocussing is accomplished with electromagnetic lenses. The beam focussing properties in the horizontal plane of the switching and analyzing magnet are also utilized.

Electrostatic fields are used to provide slight beam deflections for alignment of the beam within the drift tube. All of these beam optic elements are designed to introduce a minimum of beam aberration or energy spread.

A large cross-section electron beam can be produced at the target plane by placing a scattering foil in the path of a well focussed beam. This technique has limitations, particularly for the evaluations described here, but has been used. An air core solenoid lens is also used with the electron beam to produce a beam convergence that will allow entry into the environmental chamber with subsequent crossover and divergence.

The solenoid lens is not a practical method of handling proton or ion beams. These beams are focussed and defocussed with electro-magnetic quadropole lenses. It should be noted that the accelerator without supplemental focussing elements provides a low emittance beam with 90% of its charged particles located within a 1 cm diameter circle. A quadropole magnet is used to supplement the focussing of the beam by the analyzing magnet. Pairs of quadropoles or quadropole doublets are used to introduce the required beam convergence for entry into the chamber. Quadropole lenses produce convergence in one plane and divergence in a 90° displaced plane. Doublet lenses with poles displaced 90° will thus permit control of circular beams and the introduction of convergence or divergence as desired.

SOLAR SIMULATOR[3]

The solar simulator (Fig. 10) uses a high pressure, compact arc, Xenon lamp as the energy source. It can be operated as high as 4.2 KW for high intensity simulation. The short term intensity is regulated by a feedback amplifier that uses the output of a solar cell in its feedback loop and controls the firing angle of a silicon controlled rectifier power supply. The long term intensity is maintained by a calibrated solar cell mounted at the same distance from the simulator as the cells being studied but outside the chamber. The solar beam is diverted by an external mirror and the lamp intensity is periodically adjusted to maintain the calibrated short circuit current. The external standard is maintained at a temperature close to ambient by a separate control system. A Lenticular lens system is used to achieve a uniform irradiance at the sample plane that is better than 2% uniform over a 23 cm by 23 cm area.

DATA ACQUISITION

It is desired to measure the current-voltage characteristics of the solar cells in their active region after each dose of radiation. Various experiments have been designed to study the effects of temperature and solar intensity during irradiation to simulate certain extra-terrestrial missions. The data system has been designed to record the data in digital form so that computer processing can be utilized. To achieve this the circuit shown in block form in Figure 11 is used in conjunction with a data acquisition system. The cell characteristic is traversed by driving current from a separate supply and measuring the voltage across the cell and the current by measuring

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[3]Spectrolab Inc., Sylmer, Calif.

the voltage drop across a precision resistor. The current is driven in stepwise fashion by an I.C. operational amplifier used as a staircase generator triggered by the data acquisition system; an I.C. voltage comparator; an I.C. integrator; an I.C. gated feedback amplifier and a power transistor. The feedback amplifier is used to modify the voltage step of the staircase generator as a function of the change in the cell current so that the data points on the I-V curve are uniformly spaced. The gating of the feedback amplifier is required to suppress the transient caused by the cell being switched by the cross-bar scanner in the data acquisition system.

In the data acquisition system each cell is assigned to a data channel. A tape controlled programmer selects the channel, the range, the integration period and the measurement mode. The current and voltage are measured simultaneously on separate digital voltmeters and are recorded on punch paper tape sequentially. The number of data points collected for each cell can be varied to suit the particular experiment. While the data acquisition system provides precision of better than ±.5% the actual precision is limited at present to ±2% due to short term fluctuations on the intensity of the simulator believed to be due to the wandering of the arc. Because of long lines necessary to connect the data acquisition system and the samples in the chamber a Kelvin connection is used to eliminate the problem of the voltage drop in the 1800 cm of wire.

A typical data run would sample and record the Faraday cup currents, the thermocouple voltages, the system pressure and the time during the particulate irradiation and the cell I-V characteristics and temperature after each irradiation. Thus from the data tape it is possible to computer generate plots of I_{sc}, V_{oc}, and Pmax vs. fluence for each cell with cell temperature and light intensity as parameters.

CONCLUSION

The Space Radiation Environment Simulator can be used to create in the laboratory a wide range of conditions that could be encountered on space missions and that could degrade solar cells, solar cell cover glasses and solar cell cover glass adhesives. Properties of these devices and materials can be studied as a function of particle fluence, simulated solar intensity and temperature over a wide range. Raw data output in digital form can be used with a computer to provide any significant type of analysis as required.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to a number of people who gave valuable inputs at various points in the design of this chamber. We owe special thanks to W. Gdula and M. Moore formerly of this center, W. Wappaus, GSFC, A. Lauer of Varian and H. Slack of Howard Slack Assoc.

TABLE 1

Pump	Max. Pumping Speed	Pressure Range
Noble-Vac-Ion.	4×10^2 l/s @ 4×10^{-6} Torr	below 10^{-3} Torr
Titanium Filament Evaporator..	1×10^4 l/s @ 1×10^{-7} Torr*	below 10^{-3} Torr
Titanium Bulk Sublimator..	7×10^4 l/s @ 1×10^{-5} Torr*	below 5×10^{-5} Torr

*Area/Conductance limited at lower pressures.

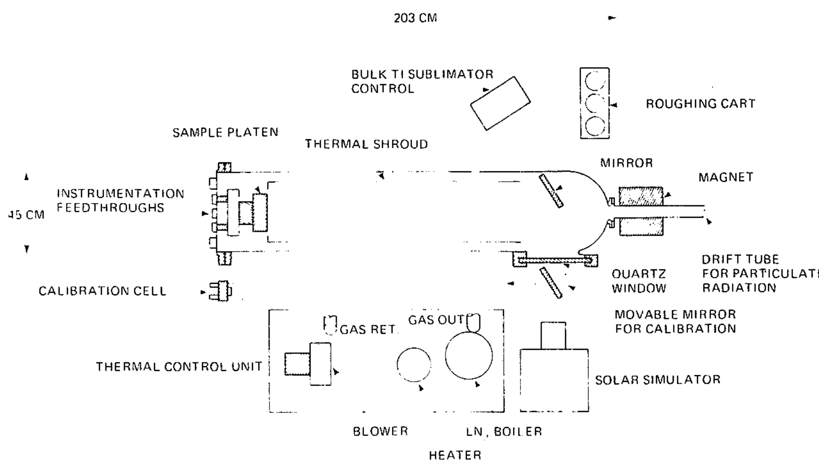

Fig. 1—Space radiation environment simulator — plan view.

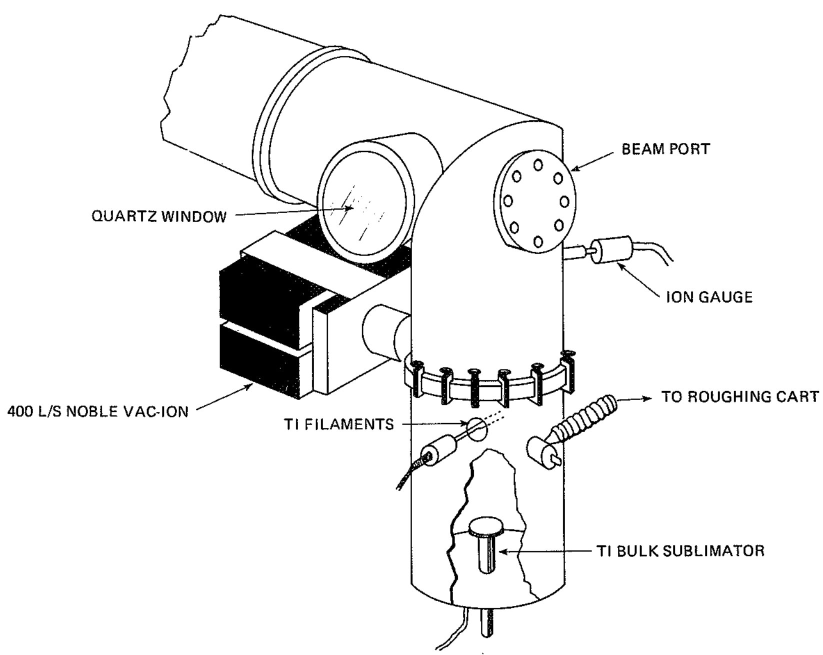

Fig. 2—Space radiation environment simulator — vacuum pumping components.

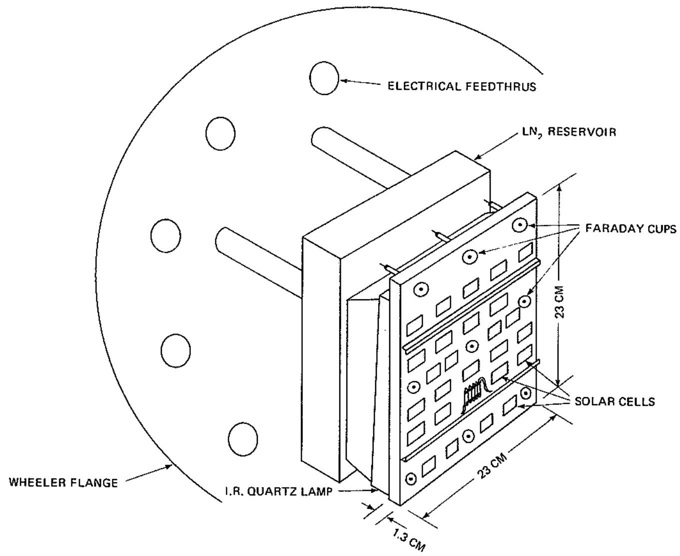

Fig. 3—Space radiation environment simulator — sample platen.

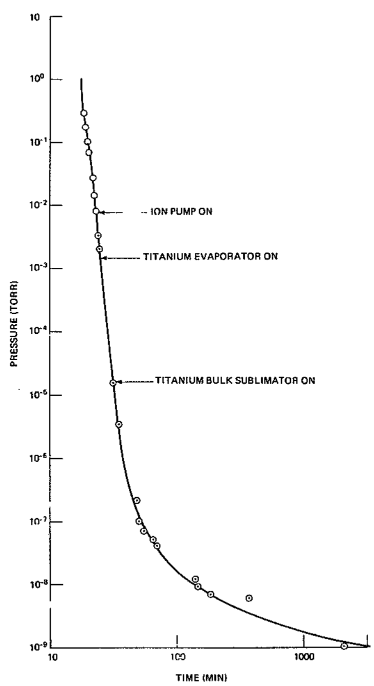

Fig. 4—Typical pump-down cycle.

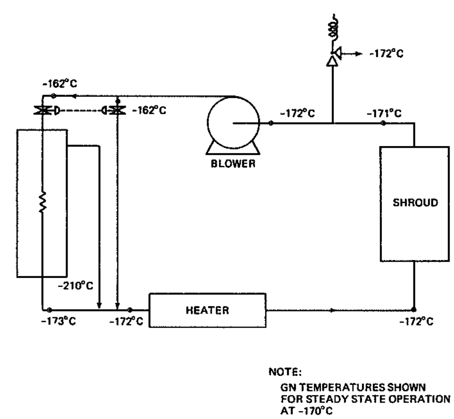

Fig. 5—Thermal control system for shroud — gas mode.

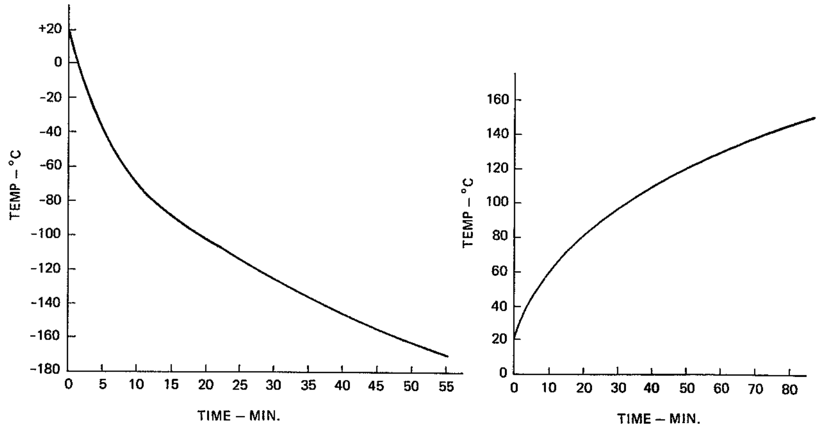

Fig. 6—Shroud transient performance.

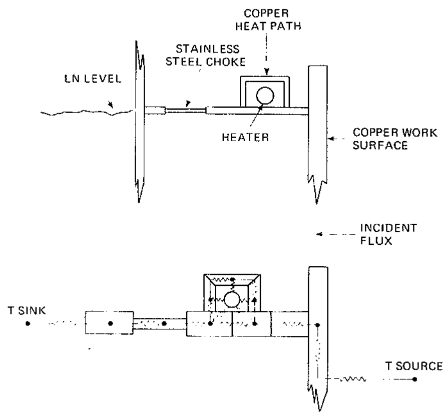

Fig. 7—Thermal mock-up of platen.

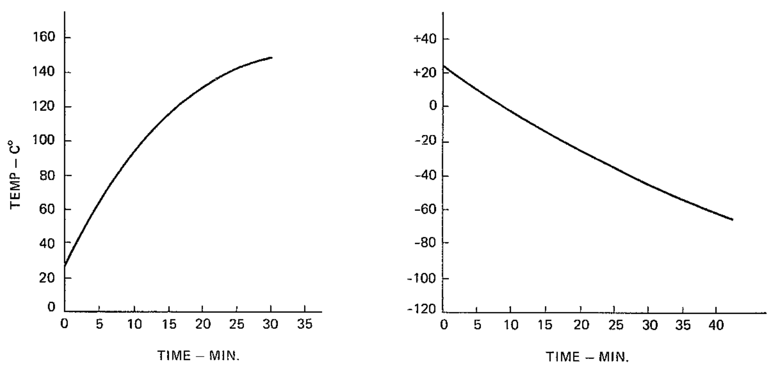

Fig. 8—Platen transient performance.

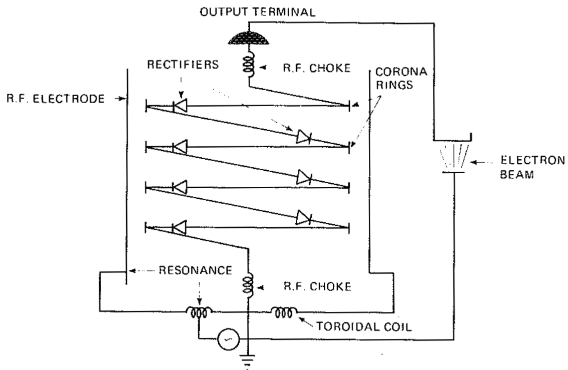

Fig. 9—Dynamitron equivalent circuit.

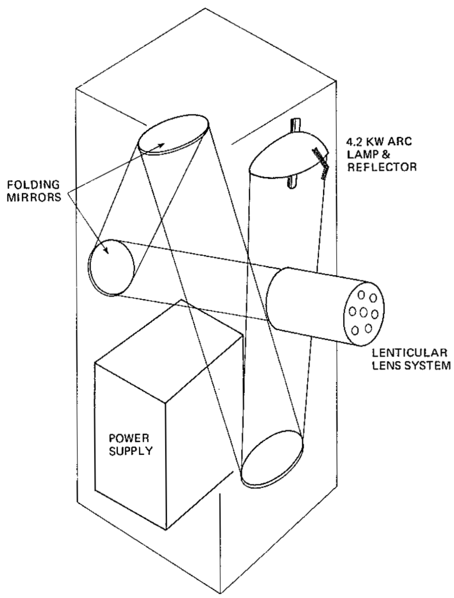

Fig. 10—Solar simulator.

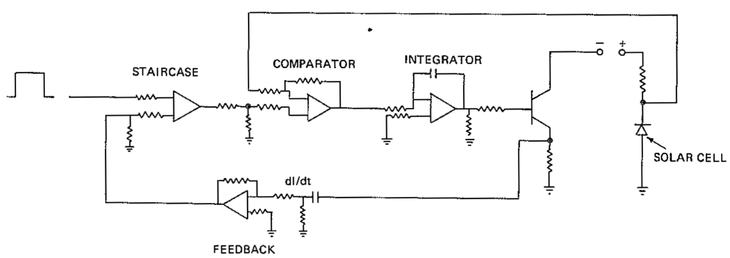

Fig. 11—Circuit for producing solar-cell I-V characteristics.